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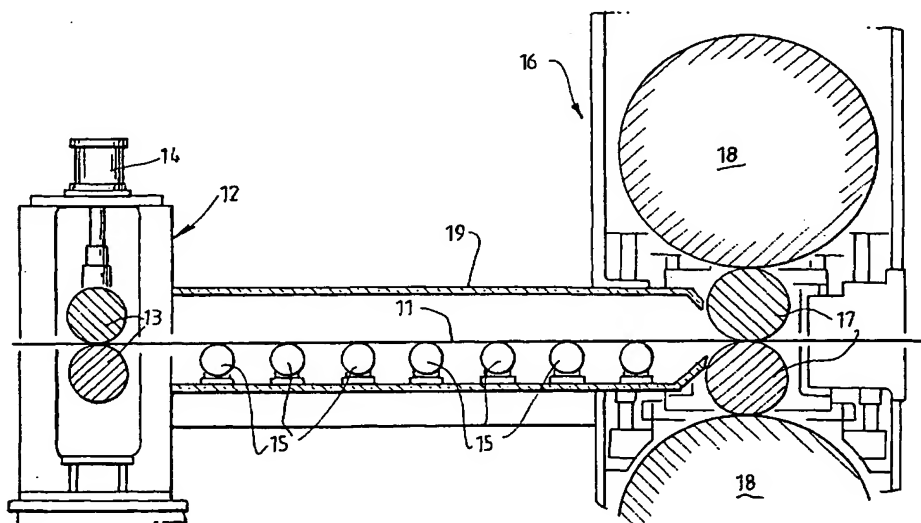(43) International Publication Date
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[Continued on next page]

(54) Title: HOT ROLLING THIN STRIP

(57) Abstract: Thin steel strip (11) is passed through a pinch roll stand (12) comprising pinch rolls (13) to a rolling mill (16) comprising a pair of work rolls (17) and upper and lower backing rolls (18). Strip (11) passes through the bite between work rolls (17) and strip squeezing forces are applied between the work rolls to reduce the thickness of the strip. Pinch rolls (13) apply tension to the strip passing to the work rolls (17). In order to minimize generation of crimping defects in the strip, the tension applied by the nip rolls (13) is high enough to ensure no part of the strip entering the work rolls is in longitudinal compression such as to exceed the buckling stress of the strip. The applied tension is sufficiently low as to produce no more than 1% strip elongation through creep. The strip may be hot rolled by work rolls (17) at a temperature in the range 700°C-1200°C.

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For two-letter codes and other abbreviations, refer to the "Guid-ance Notes on Codes and Abbreviations" appearing at the begin-ning of each regular issue of the PCT Gazette.

HOT ROLLING THIN STRIP

Background and Summary of Invention

5   This invention relates to the hot and warm rolling of thin strip typically above 700°C. It has particular, but not exclusive, application to in-line rolling of thin steel strip produced by direct casting with a twin roll caster where shape correction of the strip is

10 important.

    Recent developments in twin roll strip casting have enabled steel strip to be produced to thickness of the order of less than 5 mm and typically 3 mm and less. Such strip can be further reduced in thickness by reduction in

15 an in-line hot rolling mill as it is produced from the caster. It has been found that when hot rolling such strip to further reduce the thickness significant defects can be generated in the strip due to crimping of the strip material on entry to the work rolls of the mill. Such

20 crimping defects may be relatively minor and appear as curved lines seen on the surface of the strip. However, particularly when rolling very thin strip, the crimped parts of the strip may become folded over prior to rolling so that parts of the strip become heavily reduced and split

25 with resulting very severe defects.

    Such crimping defects have been found to be due to variations in the strip thickness and the resulting reduction across the width of the strip. Typically, the center part of the strip may be subjected to higher

30 percentage reduction than the strip edges, or "waves" may occur across the width of the strip. The latter manifests as "waves" along the length of the strip. The action of reduction through the rolling mill creates more backwards slip in the thicker portions of the strip relative to the

35 thin portions of the strip. The thicker parts of the strip will therefore be subject to lengthwise compression whereas the thinner parts will be subjected to tension, and that will cause buckling. The buckles are then rolled into the strip to create downstream shape defects. In extreme cases

40 the strip may completely fold over at the buckles and the folded over material is rolled-in to produce severe

defects. Where variations in strip thickness across the strip width are localized to small parts of the strip width, the result can be localized crimping of the strip. The extent of the crimping is related to the size of the

5 difference in thickness across the strip width and the extent of the strip width affected by the difference in reduction.

We have found that crimping during hot rolling of thin steel strip of less than about 3 mm thickness can be

10 substantially controlled by ensuring that the strip entering the rolling mill is subjected to tension within specific limits. More specifically, we have found it is possible by applying certain tension that buckling of the strip of the kind which will initiate crimping can be

15 avoided, while at the same time, maintaining the tension below an upper limit to avoid excessive strip creep (leading to necking or tearing) that will damage the strip.

An illustrative embodiment of the invention provides a method of shape correction by hot rolling of

20 thin steel strip of the type most typically produced by direct casting using a twin roll caster, comprising feeding the strip through a roll bite between a pair of work rolls, applying strip squeezing forces between the work rolls to reduce the thickness of the strip, and applying tension to

25 the strip passing to the work rolls sufficiently high to ensure no part of the strip entering the work rolls is in longitudinal compression such as to exceed the buckling stress of the strip and sufficiently low as to produce no more than 1% strip elongation through creep. The tension

30 allowable to produce no more than 1% elongation through creep was determined as described in "Effect of Carbon Content on Plastic Flow of Plain Carbon Steel at Elevated Temperatures", P.J. Wray, American Society for Metals and the Metallurgical Society of AIME, Vol 13 (Jan 1982).

35 While the strip may be in excess of 2.5 mm thick prior to rolling, it may also have a pre-rolling thickness of as low as about 0.5mm or less.

The strip may be hot rolled at a temperature of at least about 700°C. The strip may also be hot rolled up

40 to a temperature of about 1200°C. The degree of reduction of the strip thickness through the work rolls is generally

- 3 -

about 35 % or less, and is determined usually by the customer choice of thickness in the final strip.

The applied tension may be such as to limit the strip elongation through creep to no more than 0.5%.

Preferably, the variation in strip thickness reduction across the strip imposed by the work rolls is sufficiently small to prevent strip shape defects and surface creasing downstream of the work rolls of more than 200 I-units. However, in some circumstances, the variation in reduction may be such as to permit downstream shape defects and surface creasing of up to 400 I-units. The produced strip will vary in shape defects across its width; these I-unit figures are the worst case shape defects and surface creasing of the strip. The rolled strip so produced is typically additionally processed after cooling in a commercial skin pass mill to produce flatter strip with shape defects and surface creasing below 100 I-units.

I-units are a measure of the flatness of the strip produced. I-units are determined by the equation:

$$I\text{-units} = (h/l)^2 \times 24.649$$

where "h" is the peak to peak amplitude, and "l" is the distance between peaks (i.e. wavelength) of the shape defects in the strip. Sometimes by convention in operation 24.649 is rounded to 25 in use of this equation in determining the I-units.

The tension is typically applied to the strip by passing it through a pair of pinch rolls in advance of the work rolls, but additional pinch rolls may be also be used downstream of the work rolls to maintain tension across the work rolls. The greater the tension at the work rolls the lesser the rolling load to achieve a given reduction.

BRIEF DESCRIPTION OF THE DRAWINGS

In order that the invention may be more fully explained, the determination of appropriate strip tensions and one form of rolling apparatus for operation in accordance with the invention will be described in some detail with reference to the accompanying drawings in which:

Figure 1 illustrates diagrammatically the typical formation of crimping defects in hot rolling thin strip of

less than 3 mm made by direct casting with a twin roll caster;

Figure 2 is a graph plotting the necessary compressive stress for buckling for a given strip thickness to width ratio and strip temperature;

Figure 3 plots upper and lower entry tension limits for typical thin steel strip when hot rolled at temperatures of 850°C to 1200°C in accordance with the present invention; and

Figure 4 illustrates part of the strip mill installation, which can be operated to hot roll thin steel strip in accordance with the present invention.

DETAILED DESCRIPTION OF THE DRAWINGS

Figure 1 diagrammatically illustrates a strip 1 passing through a roll bite between a pair of work rolls 2 of a rolling mill in circumstances where there is upstream buckling at the locations 3 which are rolled in to produce downstream defects 4 (shape defects and surface ceasing, or crimping). This illustrates the problem addressed by the present invention.

As the lateral variation in elongation after rolling is also the downstream shape defect it can be shown, as discussed in the Appendix, that the magnitude of crimping must be less than this shape defect. In particular, the Appendix to this specification shows that the "crimping" strip strain $|d\varepsilon_0|$ at mill entry is given by:

$$|d\varepsilon_0| \leq |d\varepsilon_s| \qquad (1)$$

where $|d\varepsilon_s|$ is the downstream shape defect magnitude expressed as an elongation strain. That is, the upstream crimping strain is always less in magnitude than the downstream shape defect strain. The downstream shape defect is easier to measure than the crimping strain and the *maximum* shape defect allowable for downstream processing is better defined, being typically less than 200 I-Units, although in some circumstances the variation in downstream shape defects may be up to 400 I-units. As the upstream crimping strain must be less in magnitude than the

downstream strip shape strain this in turn gives the
maximum expected crimping strain for such strip under
normal rolling conditions.

5   It should be noted that the problem addressed by
the present invention is directed to thin strip such as
that made by casting with a twin roll caster, where the
shape defects are not uniform across the width of the
strip. If the strip is sufficiently thick then buckling
will not occur despite the transverse variation in
10   elongation due to the strip's flexural rigidity. The
minimum buckling strain has previously been empirically
related to the strip thickness and width for the case of
Shape Defects by Somers *et al* in the following publication:
Somers R.R. et al (1984), "Verification and Applications of
15   *a Model for Predicting Hot Strip Profile, Crown and*
Flatners", Iron and Steel Engineer, Sept. pp35-44. The
same theory can be applied to upstream "crimping". Figure
2 shows the necessary corresponding compressive stress for
buckling for a given strip thickness to width ratio and
20   strip temperature.

          For strips of less than 2.5 mm thickness and
greater than 1000 mm width, the necessary compressive
stress is less than 2 Mpa (i.e. mega pascals). The
buckling stress will easily be surpassed for typical
25   present shape defects, which are of order 5 to 10 Mpa in
stress. For thicker strip of 10 mm, the buckling stress is
of order 10 to 20 MPa and hence buckling is unlikely to
occur. Also, the problem is typically not present in
conventional rolled thin strip since the thin strip is
30   produced by compression through previous rolling mills and
the resulting strip is relatively uniform thickness profile
across the width of the strip with a center crown.

          The applied tension necessary to avoid crimping
provides no part of the strip is in compression, and any
35   compression is less than the buckling limit of the strip.
The strip must be elastically elongated so that the shorter
sections of the strip are stretched to match the longer
more elongated regions. This tension stress t is given by
the product of the Elastic Modulus E and the worst case
40   "crimp" expressed as a compressive strain $d\varepsilon_0$.
Using Equation (1) above, an entry tension can be derived

in terms of the downstream shape defect as:

$$t = E|d\varepsilon_0| \approx Ed\varepsilon_s$$

5   If the maximum allowable shape defect is 200 I-Units, or 0.2% compressive elongation, then the necessary applied tension stress t to avoid crimping can be calculated. The strip elastic modulus is temperature dependent and for the present purpose was modeled from

10 experimental data by

$$E = 41 \exp(-T/330) GPa$$

where T is temperature in degrees Celsius. The minimum

15 applied entry stress to avoid crimping for 200 and 400 I-Units downstream shape defects is shown in Figure 3 for the Elastic Modulus at the different strip temperatures for a typical silicon/manganese killed steel strip as produced by a twin roll caster. That steel may have the composition:

20

Carbon	0.05-0.10% by weight
Manganese	0.50-0.70% by weight
Silicon	0.20-0.30% by weight
Aluminum less than	0.008% by weight

       Figure 3 shows an extreme case with 400 I-Units shape defect. This extra tension may be necessary at

25 "head" ends of casting and rolling before steady state control conditions are reached.

       The maximum applied tension must be such as to avoid excessive strip creep (leading to necking or tearing) of the strip. Creep will always occur to some extent for

30 rolling of hot strip under tension. The tension stress necessary to cause a given degree of strain is dependent on the temperature and to a much lesser extent the strain rate. For a given maximum strain deemed allowable the maximum tension stress can be predicted for a strain rate

35 with the use of a Creep Model. For the present case the

creep stress was determined by the Model

$$t(MPa) = 3000\left(\frac{\varepsilon \max}{100}\right)^{0.23}\left(\frac{u\varepsilon \max}{60l}\right)^{0.09}\exp(-T/330)$$

5   where ε_{max} is the maximum percentage creep strain permitted,
u is the strip speed in meters/min and l is the length in
meters the strip is under tension. The coefficients were
found from experimental data for this grade of steel. This
is shown as upper stress limits in Figures 3 for both 0.5%
10   and 1% maximum elongation creep strains between the tension
device and rolling mill spaced 1 m apart at strip speeds of
60m/min. It was found that for a doubling/halving of the
strain rate, brought about by a similar variation in the
casting velocity, for example, then this stress varied by
15   only 5%.
       Figure 3 shows the tension windows for thin strip
(less than 3 mm) that should ensure no crimping but also
avoid excessive strip creep over the temperature range of
900° C to 1200° C. The maximum downstream shape can be
20   assumed to be either 200 I-Units or 400 I-Unit. The former
is the typical upper limit. The latter is representative of
a typical extreme cases such as might be present at head or
tail ends of a cast or during tracking problems. The upper
limits of the anti-crimping tension were such that the
25   elongation creep is less than 0.5% or 1% elongation. The
allowable tension to produce no more than 1% elongation
through creep, as indicated above, was determined as
described in "Effect of Carbon Content on Plastic Flow of
Plain Carbon Steels at Elevated Temperatures", by P.J.
30   Wray, American Society for Metals and the Metallurgical
Society of AIME, Vol. 13A (Jan 1982).
       These results are for manganese/silicon-killed
steel as discussed above. For aluminum-killed steel the
maximum tensions would typically be reduced by 25% but this
35   would depend on the strip chemistry. Typical aluminum
killed steel may comprise about 0.06% by weight of carbon,
about 0.25% by weight manganese, about 0.15% by weight of
aluminum.

It will be seen that the necessary tension increases with a lowering of the strip temperature due to increase in the Elastic Modulus. Typically, the lower tension stress limits ranged from about 5 (11) MPa for

5   900□C to 2 (4) MPa for 1200°C for 200 (400) I-Unit shape respectively. The upper tensions were 37 to 15 MPa over the same temperature range for 0.5% maximum strip elongation.

The same tension stress limits are expected to

10   apply to stainless steel 304.

Figure 4 illustrates part of a rolling mill installation, which can be operated in accordance with the present invention. In this rolling mill installation a thin steel strip 11 is passed through a pinch roll stand 12

15   comprising a pair of pinch rolls 13 to which strip gripping forces are applied by a pair of hydraulic cylinder units 14 disposed one to each side of the pinch roll stand.

After passing through pinch roll stand 12 the strip 11 is supported on a table formed by a succession of

20   rollers 15 across which it passes to a rolling mill 16 comprising a pair of work rolls 17 disposed one above the other and a pair of upper and lower backing rolls 18. Strip reduction forces are applied between the work rolls 17 by means of hydraulic cylinder units (not shown)

25   disposed at the two sides of the rolling mill and acting through the upper backing rolls 18. Between pinch roll stand 12 and rolling mill stand 16; the strip is held within a sealed enclosure 19.

In accordance with the present invention the

30   pinch roll is operated to apply a tension in the strip entering the rolling mill which is sufficiently high to prevent crimping, but low enough to avoid excessive creep.

The illustrated apparatus is advanced by way of example and as indicative of the best method of performance

35   of the invention presently known to the applicant. However other forms of apparatus would be feasible. In particular, although a single pair of pinch rolls are a simple and efficient means of developing tension in the strip in advance of the work rolls, it would be possible to use

40   other means of generating tension such as a series of pinch rolls or bridle rolls, and preferably pinch rolls, a

series of pinch rolls or bridle rolls downstream from the
rolling mill.

<u>APPENDIX</u>

5   CORRESPONDENCE BETWEEN SHAPE AND CRIMPING

        Shape defects occur when reduction through a
rolling mill is not uniform across the strip width and
hence local regions with more reduction produce longer
10   strip downstream than the reference. This longer strip
will locally buckle. If dr is the local variation in the
degree of proportional thickness reduction, and $d\varepsilon_s$ is the
local variation in strip strain extension, proportional to
strip length (shape), then by conservation of strip mass
15   flow we can show that

$$d\varepsilon_s = dr/(1-r)$$

where r is the reference (mean) strip reduction. Strip
20   shape tolerance limits are generally well defined.
        Now let us consider the region of the rolling
mill and assume the strip enters this region with a uniform
speed across the width and hence no upstream crimping. If
there is a non-uniform reduction then from mass flow
25   conservation the strip must exit the rolling region at non-
uniform speeds depending on the extension (shape)
variation. In particular from mass flow considerations the
exit speed u_{exit} can be expressed in terms of the entry
speed u_{entry} and thickness h_{entry} together with the exit
30   thickness h_{exit}. Mathematically we can write:

$$u_{exit} = u_{entry}h_{entry}/h_{exit} = u_{entry}/(1-r)$$
$$du_{exit} = u_{exit}dr/(1-r) = u_{exit}d\varepsilon_s$$

where du_{exit} is the variation in strip exit speed and by the
35   second equation is dependent on the downstream strip shape.
A larger reduction causes a faster exit speed. In general
this situation cannot occur as the roll and strip speeds

are closely related and an arbitrary variation of strip
exit speed from the strip shape will wrongly imply
variation in roll speed along its axis. The assumption
that strip entry speed near the rolling region being
5   uniform along the strip width can therefore not be true.
        Let us now assume the other extreme where the
strip exit speed is uniform. Using the same argument the
strip entry speed into the rolling region is given by

$$u_{entry} = (1-r)u_{exit}$$
$$du_{entry} = -u_{exit}dr = -u_{entry}dr/(1-r) = -u_{entry}d\varepsilon_s$$

10

where du_{entry} is the variation in entry speed. A downstream
strip shape defect of the form of local relative strip
extension therefore reduces the entry speed. Far upstream
15   from the rolls the strip speed is uniform and so locally
the strip must slow (backward slip) and become compressed
as it enters the rolling region. The corresponding strip
compressive (negative tension) stress due to the downstream
shape is then
20

$$t = Ed\varepsilon_0 = E\frac{du_{entry}}{u_{entry}} = -Ed\varepsilon_s$$

where $d\varepsilon_0 = du_{entry}/u_{entry}$ is the upstream crimping strain. We
now have a formula relating to the upstream tension
variation to the downstream shape defect. If this
25   compressive stress is too large then buckling will occur
upstream with the undesirable effects mentioned previously.
To overcome this buckling, a positive entry tension may be
added of magnitude equal to the greatest compressive
tension from the shape defect.
30   The above two scenarios are the extreme cases and
in practise conditions (about half way) between occurs
causing variation in strip speed (and tension) near the
rolls both upstream and downstream of half the above
magnitude. The above stress formula is therefore the upper
35   limit for upstream compression but can still be used giving
an inbuilt safety margin.

CLAIMS:

1.   A method of hot rolling thin steel strip comprising:

5

         feeding the strip through a roll bite between a pair of work rolls,

10   applying strip squeezing forces between the work rolls to reduce the thickness of the strip,

         and applying tension to the strip passing to the work rolls sufficiently high to avoid buckling stress in the strip entering the work rolls, and sufficiently low as

15   to produce no more than 1% strip elongation through creep.

2.   A method as claimed in claim 1, wherein the strip is no more than 3 mm thick prior to feeding to the work rolls.

20

3.   A method as claimed in claim 2, wherein the strip thickness is in the range of 0.5 mm to 2 mm prior to feeding to the work rolls.

25   4.   A method as claimed in claim 1, wherein the strip is hot rolled at a temperature in the range of 700° C to 1200° C.

5.   A method as claimed in claim 2, wherein the strip

30   is hot rolled at a temperature in the range of 700° C to 1200° C.

6.   A method as claimed in claim 3, wherein the strip is hot rolled at a temperature in the range of 700° C to

35   1200° C.

7.   A method as claimed in claim 4, wherein the strip is hot rolled at a temperature in the range 900° C to 1200° C.

40

8.   A method as claimed in claim 5, wherein the strip is hot rolled at a temperature in the range 900° C to 1200° C.

45   9.   A method as claimed in claim 6, wherein the strip is hot rolled at a temperature in the range 900° C to 1200° C.

- 12 -

10.   A method according to claim 1, wherein the
applied tension is such as to limit the strip elongation
through creep to no more than 0.5%.

11.   A method according to claim 1, wherein the
variation in strip thickness reduction across the strip as
imposed by the work rolls is such that the strip shape
defects downstream of the work rolls are no more than 400
I-units.

12.   A method according to claim 11, wherein said
variation in strip thickness reduction is such that the
strip shape defects downstream of the work rolls is no more
than 200 I-units.

13.   A method according to claim 1, wherein tension is
applied to the strip by passing said strip through a pair
of pinch rolls in advance of the work rolls.

14.   A method according to claim 1, wherein the strip
is a manganese/silicon killed steel strip of thickness in
the range 0.5 mm to 3 mm,

the strip is hot rolled in the temperature range
900° C to 1200° C,

and the applied tension is within an operating
range between maximum and minimum values defined by:

tension max = maximum allowable elongation at the
rolling temperature, and

tension min = maximum strip buckle stress
allowable at the rolling temperature.

15.   A method of hot rolling thin steel strip produced
by direct casting by a twin roll caster comprising:

feeding the strip through a roll bite between a
pair of work rolls,

applying strip squeezing forces between the work
rolls to reduce the thickness of the strip,

and applying tension to the strip passing to the
work rolls sufficiently high to avoid buckling stress in

the strip entering the work rolls, and sufficiently low as
to produce no more than 1% strip elongation through creep.

16.   A method as claimed in claim 15, wherein the
strip is no more than 3 mm thick prior to feeding to the
work rolls.

17.   A method as claimed in claim 16, wherein the
strip thickness is in the range of 0.5 mm to 2 mm prior to
feeding to the work rolls.

18.   A method as claimed in claim 15, wherein the
strip is hot rolled at a temperature in the range of 700° C
to 1200° C.

19.   A method as claimed in claim 16, wherein the
strip is hot rolled at a temperature in the range of 700° C
to 1200° C.

20.   A method as claimed in claim 17, wherein the
strip is hot rolled at a temperature in the range of 700° C
to 1200° C.

21.   A method as claimed in claim 18, wherein the
strip is hot rolled at a temperature in the range 900° C to
1200° C.

22.   A method as claimed in claim 19, wherein the
strip is hot rolled at a temperature in the range 900° C to
1200° C.

23.   A method as claimed in claim 20, wherein the
strip is hot rolled at a temperature in the range 900° C to
1200° C.

24.   A method according to claim 15, wherein the
applied tension is such as to limit the strip elongation
through creep to no more than 0.5%.

25.   A method according to claim 15, wherein the
variation in strip thickness reduction across the strip as
imposed by the work rolls is such that the strip shape
defects downstream of the work rolls are no more than 400
I-units.

26.   A method according to claim 25, wherein said
variation in strip thickness reduction is such that the

- 14 -

strip shape defects downstream of the work rolls is no more
than 200 I-units.

27.   A method according to claim 15, wherein tension
5   is applied to the strip by passing said strip through a
pair of pinch rolls in advance of the work rolls.

28.   A method according to claim 15, wherein the strip
is a manganese/silicon killed steel strip of thickness in
10   the range 0.5 mm to 3 mm,

the strip is hot rolled in the temperature range
900° C to 1200° C,

15   and the applied tension is within an operating
range between maximum and minimum values defined by:

tension max = maximum allowable elongation at the
rolling temperature, and
20
tension min = maximum strip buckle stress
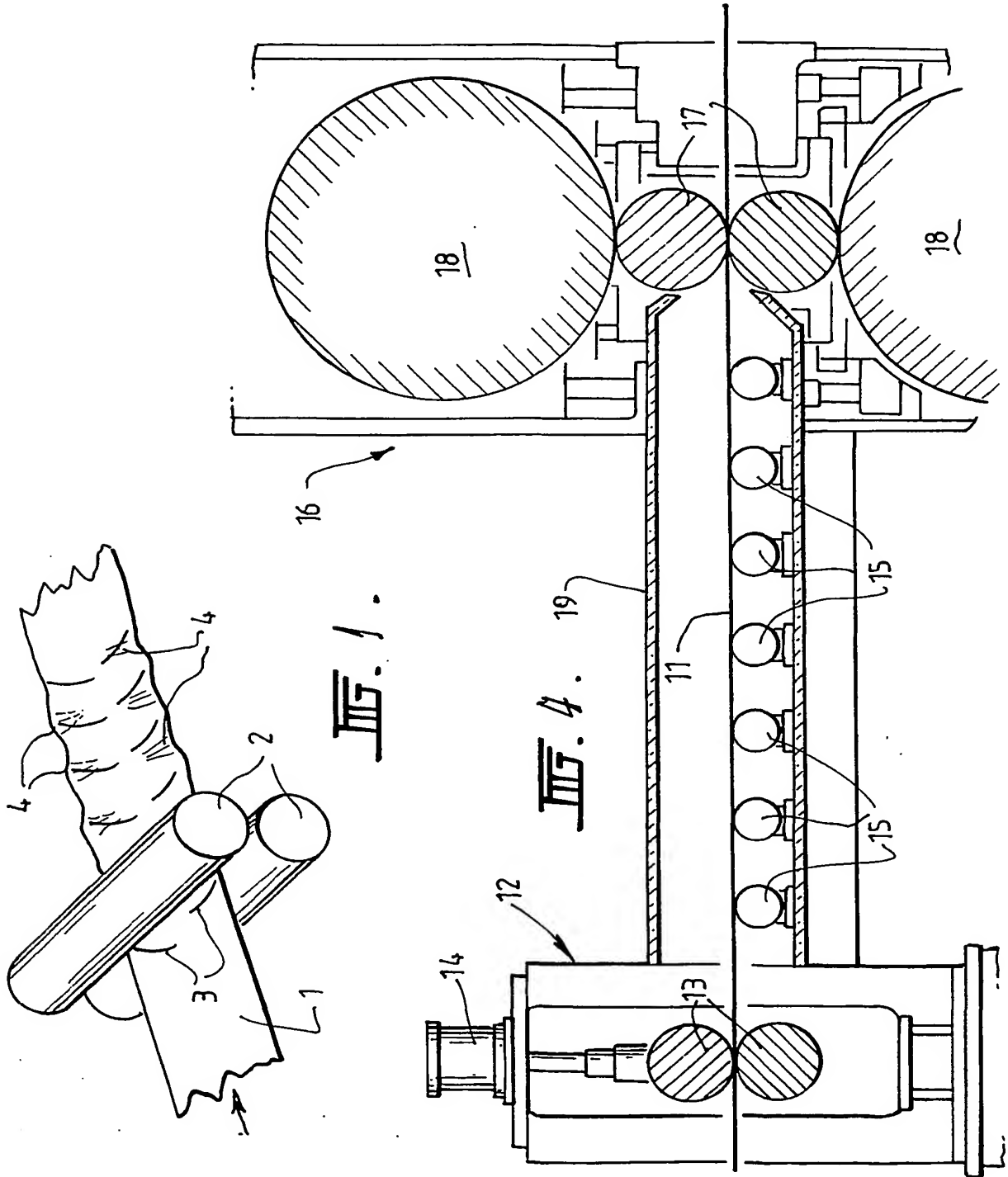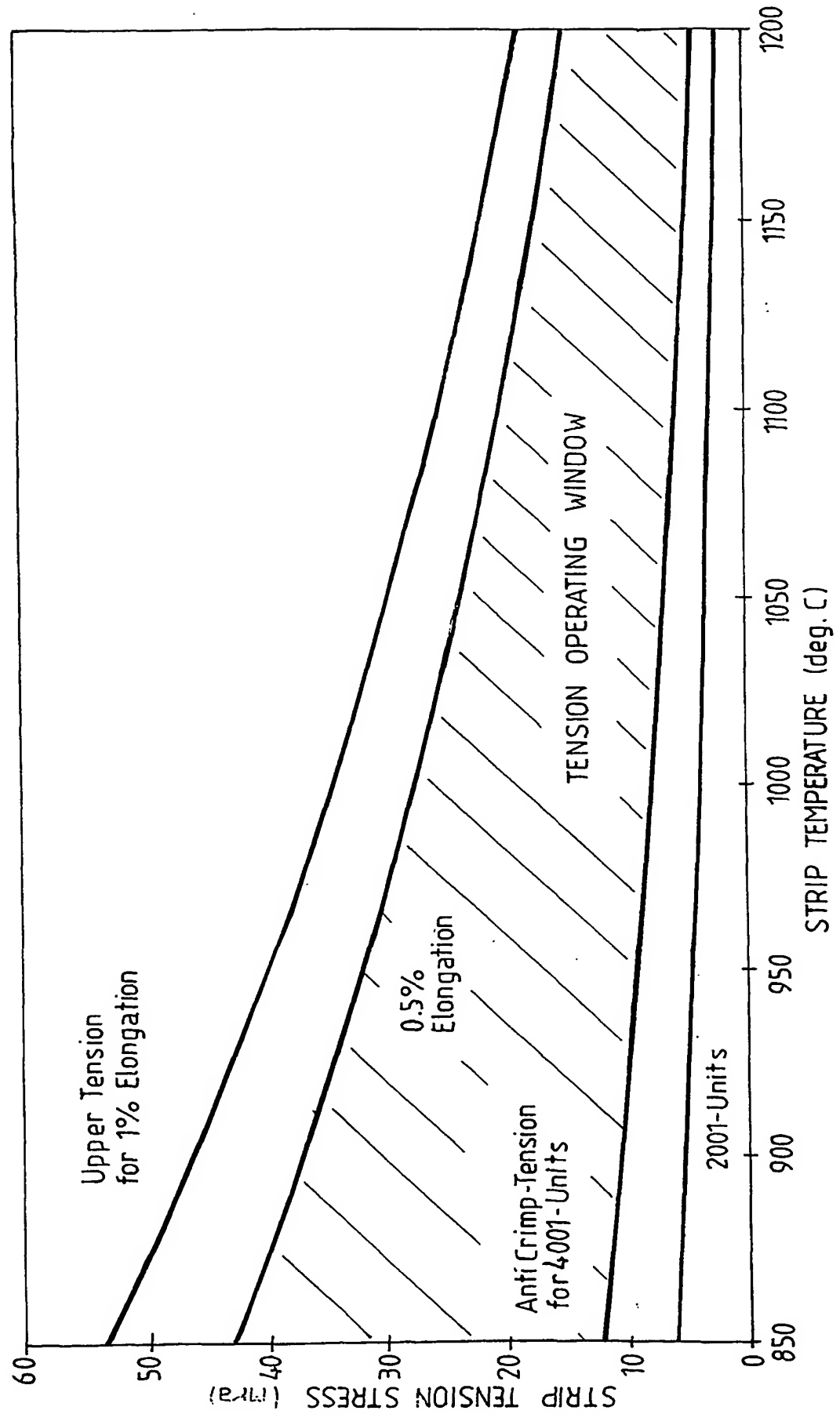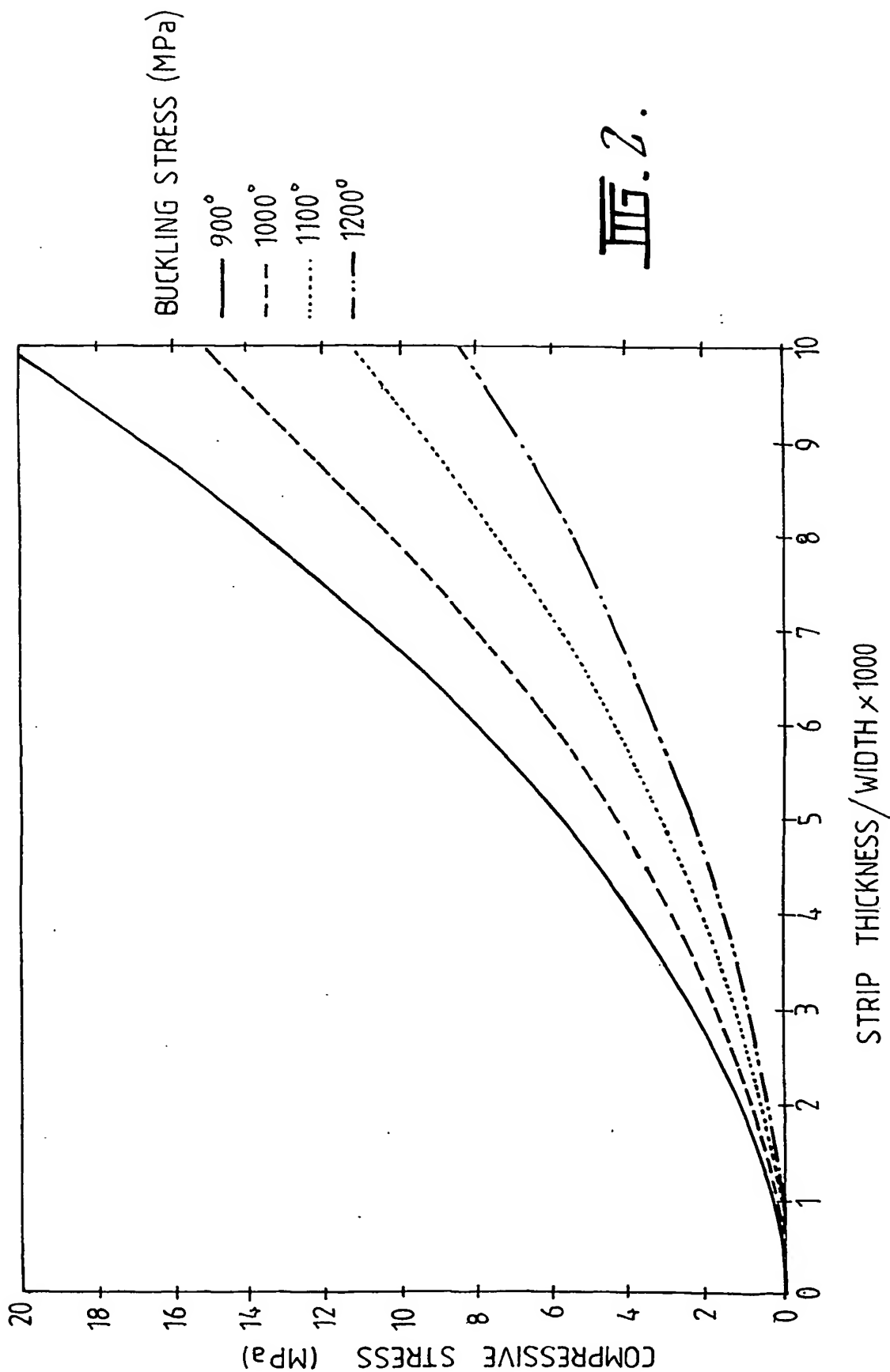allowable at the rolling temperature.

FIG. 1.

FIG. 4.

FIG. 3.

FIG. 2.

A.	CLASSIFICATION OF SUBJECT MATTER

Int. Cl. [7]:   B21B 1/26, 37/48, 37/56, 37/58

According to International Patent Classification (IPC) or to both national classification and IPC

B.	FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC[7] AS ABOVE

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
NIL

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
DWPI and JAPIO: IPC As above and key words creep, buckle, tension, elongate, stress

C.	DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	Patent Abstracts of Japan, JP 63-052702 A (Hitachi Ltd.), 5 March 1988 Abstract	1-28
X	Patent Abstracts of Japan, JP 58-006706 A (Hitachi Ltd.), 14 January 1983 Abstract	1-28
A	Patent Abstracts of Japan, JP 08-192210 A (Sumitomo Metal Ind. Ltd.), 30 July 1996 Abstract	1-28

[X] Further documents are listed in the continuation of Box C	[X] See patent family annex

*	Special categories of cited documents:	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance		
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Date of the actual completion of the international search	Date of mailing of the international search report
27 June 2001	4 July 2001
Name and mailing address of the ISA/AU

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C (Continuation).	DOCUMENTS CONSIDERED TO BE RELEVANT	
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	DE 4413913 A1 (Krupp Hoesch Stahl AG), 3 November 1994 Whole Document	1- 28

International application No.
PCT/AU01/00604

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report			Patent Family Member
JP	63052702	NONE	
JP	58006706	NONE	
JP	08192210	NONE	
DE	4413913	NONE	

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